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The impacts of policies to reduce CO_2 emissions within the concrete supply chain

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ABSTRACT

The production of concrete is a significant source of global carbon dioxide (CO_2) emissions that contribute to climate change. Many technical solutions exist for reducing emissions along the concrete supply chain. However, wide scale adoption of these technologies is hindered by a market failure – the cost of greenhouse gas emissions is not adequately reflected in cement and concrete transactions. Here, we compare three instruments meant to correct this critical market failure, including: 1) carbon-pricing policies, such as carbon taxes and cap-and-trade programs; 2) command and control policies; and 3) voluntary incentives. We evaluate each policy instrument for its capacity to reduce emissions cost effectively, guarantee emission reductions, spur technological innovation, and generate revenue. Our analysis shows that these criteria favor carbon pricing policies. However, cement and concrete markets are often concentrated and trade exposed. Therefore, regulators should design pricing policies that both combat leakage and do not limit production below socially optimal levels.

1. Introduction

Concrete has transformed the planet in several profound ways. As an inexpensive and durable building material, it has facilitated the upward and outward expansion of the built environment. Its use is so widespread it is only surpassed by fresh water in terms of material consumption [1]. In 2012, worldwide concrete consumption was estimated to have topped 10 billion cubic meters [2]. The production of concrete also carries a significant greenhouse gas (GHG) footprint, with commensurate implications for Earth's climate. Based on data reported for 2012, concrete production was responsible for approximately 8.6% of all anthropogenic carbon dioxide (CO_2) emissions in that year [2]. Climate change, driven by high concentrations of CO_2 and other GHGs in the atmosphere, will have a significant negative effect on human welfare. Increasing global average temperatures will have costly impacts on society such as: reduced agricultural yields; increased human illness and premature mortality; reduced freshwater availability; and increased energy needs, among others [3].

Numerous studies have modeled the economic damages associated with climate change. A meta-analysis of the literature reveals the estimated marginal costs of emitting an additional ton of CO_2 equivalent (CO_2e) GHG—known in the literature as the social cost of carbon (SCC)—center around $116 per metric ton [4–6]. The SCC estimated by United States (U.S.) regulatory agencies for analysis is more conservative at $36 per metric ton in 2007 dollars [7]. For perspective, it is estimated that the global concrete industry emits more than 2.7 gigatons (Gt) of CO_2e annually [2], which translates to $97 billion in economic damages based on the conservative SCC developed by the U.S. agencies.

Many of the carbon-reducing options available along the concrete supply chain require significant new capital investments or costly new processes, both of which translate into a higher unit cost for end products. Even when changes do not translate into higher costs; the incumbent industry is not likely to make changes without an incentive to do so. Currently, incentives to change are insufficient because the damages to society caused by GHG emissions are borne neither by buyers nor sellers of concrete products, and can be ignored when making purchasing decisions. The market's inability to adequately compensate for those social damages is a market failure known as a negative externality. Because of this, social welfare improvements are only possible through regulatory intervention. GHG-related externalities are not unique to concrete production and have been the basis for both energy sector and economy-wide policy interventions.

Without significant reductions in the carbon intensity of concrete production, emissions will continue to grow with global demand. By 2030, urban land cover will increase by 120 million hectares, nearly tripling the global urban land area since 2000 [8]. Much of this growth in the built environment will be met through the production of

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additional concrete, providing a serious challenge for policymakers and planners working to balance urban development with GHG reductions.

Globally, policymakers have sought to reduce GHG emissions to lessen the impact of climate change. Much of the early policy focus has been on the fossil fuels and energy sectors, which are the most significant global contributors to GHG emissions. Many of these policies indirectly impact the concrete supply chain by imposing additional energy and transportation costs. More importantly, some jurisdictions have made economy-wide efforts to curb GHG emissions in a manner that more directly impacts the concrete supply chain. For example, several jurisdictions have adopted carbon cap-and-trade programs (most of which directly regulate cement production emissions), including 32 European countries, and subnational jurisdictions within the U.S., Canada, and China [9]. Policymakers seeking to reduce GHG emissions may also employ prescriptive policy instruments to achieve targeted GHG reductions from concrete production, such as carbon intensity standards specifically for concrete products.

Research has identified the significant GHG emissions impact of the cement and concrete industry and has provided a number of technical solutions to address this growing problem [1]. This paper builds on that work by providing a framework for understanding how new or expanded GHG emission reduction policies will impact the cement concrete supply chain.

We begin with an overview of the lifecycle sources of GHG emissions along the concrete supply chain (Section 2.1) and the technical solutions for reducing emissions at each stage of the process (Section 2.2), including utilizing renewable energy; alternative fuels; energy efficiency; supplementary cementitious materials; alternative cements; material use efficiency; recycled concrete; and carbon capture, utilization, and storage. We then provide a summary of the existing and potential policy instruments that may be employed to govern GHG emissions from concrete production (Section 3), including carbon-pricing (Section 3.1), command-and-control policies (Section 3.2), and incentives (Section 3.3). To judge the societal tradeoffs between policy instruments, we analyze the performance of each with respect to cost-effectiveness (Section 4.1), control over emissions reduction (Section 4.2), technological innovation (Section 4.3), and revenue generation (Section 4.4). The paper closes by highlighting the societal benefits of using cap-and-trade programs and carbon emission taxes rather than other policy strategies (Section 5).

2. Background

2.1. Lifecycle analysis of concrete production

Lifecycle CO_2 emissions for concrete products vary greatly by region and manufacturer. More specifically, emissions vary systematically with regional electricity generation mix, production efficiencies adopted by the manufacturer, fuel types used for pyro-processing, and the amount of cement that goes into the final product. There is a wealth of lifecycle assessment literature on the CO_2 emissions of concrete products, but there are few peer-reviewed studies documenting the lifecycle emissions of concrete production from cradle-to-gate for specific geographies (see Van den Heede and De Belie [10], Gursel et al. [11], and Vieira et al. [12] for literature reviews).

The cradle-to-gate system boundary includes extraction and processing of raw materials, transportation of raw materials to production facilities, and concrete plant operations (i.e., mixing, conveying, and pumping of concrete ingredients and mixtures). To the authors' knowledge, lifecycle assessments published in peer-reviewed journals that explicitly account for each of these activities have been conducted in Australia [13–16]; China [17,18] Iran [19], South Korea [20], Serbia [21], Singapore [22], and the U.S [23]. Of these studies, Turner and Collins [16] provide the most disaggregated account of CO_2 emissions at each stage along the concrete supply chain, including emissions between the factory gate and the construction site, which are summarized in Fig. 1.

Across studies, cement production is consistently identified as the greatest source of CO_2 emissions along the concrete supply chain. Cement is GHG intensive to produce for two reasons. First, raw materials (limestone, clay, and sand) must be heated in a kiln to approximately 1450 °C to form an intermediate material known as clinker, which is then crushed into a powder and mixed with gypsum to form Ordinary Portland Cement [24]. Achieving those high temperatures requires significant quantities of fuel; and coal is the dominant fuel source worldwide [25]. Second, the thermal decomposition (calcination) of limestone (calcium carbonate) into lime (calcium oxide) during the production of clinker releases waste CO_2. The chemical reaction for this process is $CaCO_3 + \text{heat} \rightarrow CaO + CO_2$.

The heating of the raw materials in the kiln to drive the necessary chemical reactions for clinker production accounts for approximately 40% of the total CO_2 emissions associated with producing cement [24]. Calcination accounts for about 50% of the emissions associated with cement [26]. The remaining emissions from cement production are split between the transport of raw materials (5%) and the equipment operations (5%) [24]. Based on the lifecycle analysis conducted by Turner and Collins [16], calcination accounts for approximately 38% of the total emissions from the production of concrete. Calcination, therefore, is the single greatest source of CO_2 emissions within the lifecycle of both cement and concrete products. Achieving emissions reductions from this process is particularly difficult because lime is an integral component of cement production and can only be sourced at scale from the calcination of limestone.

Once a concrete product begins its useful life as a building material, a portion of the CO_2 emissions lost during calcination are re-absorbed from the atmosphere through a chemical reaction called carbonation, in which CO_2 enters the pores of the concrete and bonds with the free lime. The chemical reaction for this process is $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$, and occurs near the exposed surfaces of concrete materials. Research at the global scale has concluded that an average of 16.1% of the CO_2 emissions created from concrete production are absorbed through carbonation during the service life of the material, with an additional 1.4% absorbed during demolition, and another 0.1% during disposal or reuse of concrete waste [27]. Quantifying the effect of carbonation on a particular concrete product is difficult because CO_2 uptake varies according to final application of the product, CO_2 diffusion processes, and the service life of the material [28]. Nevertheless, the effects of carbonation present a pathway for achieving negative CO_2 emissions, assuming that CO_2 emissions can be eliminated or sequestered at other stages of the concrete supply chain [29].

2.2. Technical solutions

There is a wide range of technical solutions for reducing CO_2 emissions during the production of concrete. As with most industrial sectors, switching to renewable sources of energy and alternative low-carbon fuels, in tandem with improvements in energy efficiency, will have the greatest impact. The remaining emissions from concrete production are chemically derived and occur during the calcination process. These emissions can be reduced by using supplementary cementitious materials, alternative cements that use less limestone, optimized manufacturing and building practices that reduce waste, and recycled concrete to supplant the need for virgin materials. Where CO_2 emissions cannot be avoided through any of these methods, the remaining waste CO_2 could be captured and sequestered in geologic storage or used as an industrial feedstock. A summary of potential technical solutions is presented below. Many of these interventions have not yet been demonstrated at scale, nor are currently cost-effective, and therefore policy tools are needed to accelerate their technical development and commercial adoption.

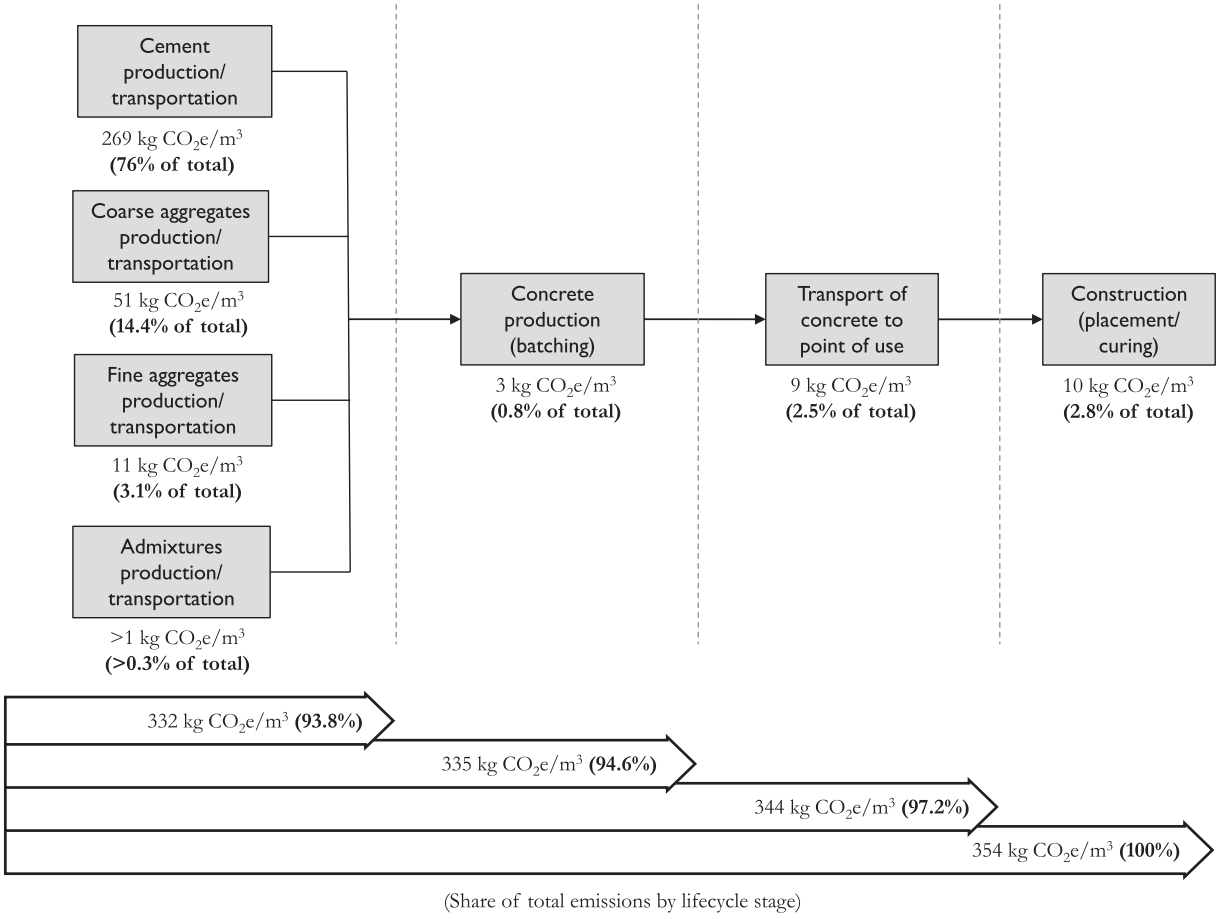
Cement production/ transportation
269 kg CO_2e/m^3 (76% of total)
Coarse aggregates production/ transportation
51 kg CO_2e/m^3 (14.4% of total)
Fine aggregates production/ transportation
11 kg CO_2e/m^3 (3.1% of total)
Admixtures production/ transportation
>1 kg CO_2e/m^3 (>0.3% of total)
Concrete production (batching)
3 kg CO_2e/m^3 (0.8% of total)
Transport of concrete to point of use
9 kg CO_2e/m^3 (2.5% of total)
Construction (placement/ curing)
10 kg CO_2e/m^3 (2.8% of total)
332 kg CO_2e/m^3 (93.8%)
335 kg CO_2e/m^3 (94.6%)
344 kg CO_2e/m^3 (97.2%)
354 kg CO_2e/m^3 (100%)
(Share of total emissions by lifecycle stage)

Fig. 1. Summary of CO_2 emissions distributed over the lifecycle of one cubic meter of concrete made with Ordinary Portland Cement with a strength capacity of 40 MPa (MPa) [16].

2.2.1. Renewable energy

In order to convert limestone into lime, heat is needed, and is typically obtained through the burning of fossil fuels. Experimental research has shown that solar thermal technologies may be able to accomplish this same goal without any CO_2 emissions. In one production model, high-flux solar irradiation is combined with a flow of methane inside a solar thermal reactor to convert limestone into lime along with two other chemical byproducts, carbon monoxide (CO) and hydrogen (H_2) [30]. In another production model, Solar Thermal Electrochemical Production, solar thermal-heated molten carbonates are electrolyzed forming oxides, which in the presence of calcium carbonate precipitate as lime and some combination of carbon (C), oxygen (O), or CO, depending on the temperature of the reaction [31]. When electrolyzed below 800 °C, the product is lime, C and O_2. When electrolyzed above 800 °C, the product is lime, CO, and O_2. Thus, in addition to reducing fossil fuel-based CO_2 emissions, both solar thermal technologies eliminate calcination-based CO_2 emissions, dramatically reducing the overall CO_2 footprint of concrete products. These experimental technologies, while promising, face geographic limitations, since concentrated solar power efficiencies are influenced by the amount of direct irradiation, which varies spatially and seasonally [32]. In addition, these technologies result in CO emissions, a harmful pollutant. To minimize the negative environmental impacts of these technologies should they become commercialized, any waste CO would need to be captured and processed into a less harmful byproduct.

Switching to renewable sources of energy (e.g., wind, solar, biogas, etc.) will also help eliminate CO_2 emissions that occur from electricity generation, which is still heavily reliant on fossil fuels. In the U.S., for example, around 66% of the electricity mix in 2015 was derived from fossil fuels [33]. Similarly, in China and India, around 77% and 80%, respectively, of the electricity mix in 2012 was derived from the burning of fossil fuels [34]. If renewable energy procurement is coupled with an electrified vehicle fleet, then CO_2 emissions could also be eliminated from the transportation of raw materials and finished products. Across the concrete supply chain, diesel fuel is the primary source of energy for transportation activities [13,20]. While the adoption of electric vehicles is growing in the light-duty vehicle sector, battery-electric technologies have only recently started to commercialize for medium-duty vehicles (8501–14,000 pounds gross vehicle weight rating) and are still in the demonstration phase for heavy-duty vehicles (> 14,000 gross vehicle weight rating) [35]. The commercialization of battery-electric vehicles will be particularly slow in off-road settings, such as open pit mining operations, given the challenges of installing charging infrastructure.

2.2.2. Alternative fuels

Switching from high-carbon fuels to lower-carbon fuels is another opportunity to reduce CO_2 emissions during the production of clinker. For example, direct substitution to natural gas from coal is estimated to reduce emissions from fuel combustion by approximately 54% [36]. A variety of waste products can also be combusted to heat the kiln, including municipal solid waste, hazardous waste, industrial and commercial residues, plastics, used tires, sewage sludge, biosolids, animal and bone meal, waste wood, and other forms of biomass [37]. The direct CO_2 emission factors of waste fuels are often considered to be zero because the input of the waste replaces fossil fuel derived energy, and the CO_2 emissions from the waste products would presumably have been released into the atmosphere anyway [38]. Additionally, by

diverting organic waste to an incinerator instead of a landfill, the release of methane (CH_4), a GHG with a global warming potential 25 times greater than CO_2 over a 100 year period [25], is averted. The use of these materials, however, may pose other negative environmental and health-related externalities. The burning of municipal solid waste, for example, results in increased mercury emissions [37]. Given this risk, more research is needed to develop alternative fuels that do not exacerbate other negative externalities.

Alternative fuels can also reduce CO_2 emissions from transportation and excavation activities, both of which rely on diesel fuel. Biodiesel, ethanol, and natural gas all have lower GHG emissions on a life-cycle basis compared to conventional diesel fuel [39]. These fuels, however, require specialized combustion engines and refueling infrastructure, and are still in the early stages of commercial deployment for many heavy-duty applications. Renewable biomethane derived from sources such as landfills, dairies, and wastewater treatment plants, as well as hydrogen and synthetic fuels produced using renewable energy, present opportunities for virtually eliminating GHG emissions from heavy-duty vehicles, but are only in the demonstration stage for most heavy-duty applications [40,41]. One advantage of using alternative fuels over battery-electric technologies is that they eliminate the need for charging. This may be particularly important during mining operations, where off-road heavy-duty vehicles depend on refueling tankers to deliver fuel to remote sites that may not be connected to an electrical grid.

2.2.3. Energy efficiency

The greatest opportunity for efficiency gains along the concrete supply chain occurs during the production of clinker. Switching from a wet to dry process can significantly reduce fuel demands at this stage [38,42]. The most efficient modern coal-fired preheater (dry process) plants use as little as 3.06 GJ of fuel energy per ton of clinker (GJ/t) [43]. Meanwhile, inefficient long rotary kilns burning wet raw materials typically operate at a heat consumption of about 6 GJ/t clinker [44]. A wide range of additional conservation measures exist for reducing fuel consumption during clinker production, and have been ranked in the literature according to their cost-effectiveness [45,46], of which eventually pay for themselves due to energy costs savings.

In addition to reducing fuel demands, reducing electricity consumption is another avenue to achieve CO_2 emission reductions. The production of coarse aggregates is a significant source of electricity consumption along the concrete supply chain [13,47,48]. Electricity is used at this stage for screening and crushing rubble collected at quarries, and can be conserved by improving the placement of explosives during the initial blasting process, creating smaller rocker fragments that reduce energy burdens on crushing equipment [13]. During the production of clinker, waste heat can be recovered through the integration of cement kilns and boilers that generate electricity, and is estimated to yield 30–45 kW h per metric ton of clinker [49]. Further down the supply chain, efficiency gains can be realized during the mixing of concrete through the installation of high efficiency motors [50]. As with any industry, proper maintenance and the replacement of aging equipment at all stages of the supply chain will lead to efficiency gains, and thus CO_2 emission reductions.

2.2.4. Supplementary cementitious materials

Replacing some limestone-based clinker with supplementary cementitious material (SCM) is another strategy to reduce CO_2 emissions from cement production. In addition to their environmental benefit, SCMs are commonly used to improve the material properties of concrete products, including compressive strength, sorptivity, permeability, water absorption, chloride penetration, sulfate resistance, carbonation, drying shrinkage, corrosion resistance, and resistance to acid attack [51]. SCMs can be added at two different points along the supply chain, either at the cement manufacturing facility or at the concrete batching facility. Once incorporated into the final concrete mix, SCMs act as a binding agent, much like limestone-based clinker, but without any of the CO_2 emissions associated with calcination. SCMs include fly ash, granulated ground blast-furnace slag (GGBFS), steel slag, silica fume, waste glass, natural pozzolan, vegetable ashes, calcined clay, and inert fillers [1]. Many of these SCMs are industrial by-products, and are considered by a number of lifecycle studies to only contribute to new CO_2 emissions at time of capture, milling, refining, and transport [13,52–54]. The use of industrial by-products as SCMs, however, depends on a steady inflow of waste from other carbon intensive industries (e.g., coal combustion, iron and steel production, etc.), which may not be readily available as nations decarbonize. SCMs derived from natural resources (e.g., clays, inert fillers, pozzolans, vegetable ashes), therefore, present a more promising means of reducing CO_2 emissions from cement production without reliance on other carbon intensive industrial sectors.

Despite their emissions benefits, SCMs cannot perfectly replace conventional Portland cement as binding agents in concrete. After a certain substitution rate, SCMs begin to compromise the desired properties of concrete, such as compressive strength, workability, and durability [55]. Substitution rates vary by material (e.g., 3–80% for GGBFS, 3–70% for fly ash, and 3–40% for silica fume) [20], which in turn result in varying levels of emissions reductions. Nonetheless, it is estimated that increasing the average level of clinker substitution in cement with SCMs to 40% could avoid up to 400 million tons of CO_2 emissions annually [1]. This would account for about 15% of the GHG emissions from global concrete production, based on estimates made by Miller et al. [2]. Achieving these emissions gains, however, requires highly regionalized SCM adoption strategies, given the variability in SCM availability.

2.2.5. Alternative cements

To fully eliminate emissions from calcination, alternative cements that do not rely on the conversion of limestone to lime are needed. Ultramafic rocks (basic magnesium silicates), for example, are globally abundant and could potentially be used instead of limestone as the principal raw material for clinker in cement production. The use of these rocks could result in negative CO_2 emissions because they are rich in magnesium oxide and have the capacity to capture CO_2 as stable magnesium carbonates [1]. This technology has not been demonstrated at scale, but has been tested in a laboratory with CO_2 from typical industrial flue gases [56]. In the near term, alternative clinkers can be used instead of Ordinary Portland Cement clinker. Belite-ye'elimite-ferrite (BYF) clinkers, for example, can be made in conventional Portland cement plants, but require 20–30% less limestone and more bauxite and other high-alumina minerals, resulting in a near commensurate level of CO_2 emissions reduction [57]. Since alternative clinkers do not completely eliminate CO_2 emissions from calcination, greater research is particularly needed in the development of limestone-free cements, such as those that are magnesium based.

2.2.6. Material use efficiency

There are several strategies for reducing the amount of cement and concrete needed in buildings altogether. While the efficient use of materials does not necessarily reduce the CO_2 emission intensity of concrete by mass, it can reduce the CO_2 emissions that are embodied in buildings. During concrete production, improvements in binder efficiency can reduce the amount of cement needed for a concrete product without necessarily reducing strength [58]. During construction, greater use of precut and preassembled components may reduce waste that occurs from concrete production at the building site [59]. Additionally, buildings can be designed in a way that minimizes the amount of concrete needed for building components, such as through the use of pre-stressed concrete members, flat slabs, and voided slabs [60]. Once a concrete structure is built, extending the service life of that structure is another means of reducing concrete consumption, especially in steel reinforced concrete structures where corrosion can occur

from the ingress of chloride ions [61]. To address this problem, the use of shrinkage reducing admixtures and corrosion inhibitors in concrete products can help improve durability [1]. Greater industrialization of the concrete manufacturing sector, especially in developing countries, can particularly accelerate many of the efficiency strategies discussed here.

2.2.7. Recycled concrete

At the end of a concrete product's useful life, it can often be recycled, offsetting some of the CO_2 emissions that occur from the processing of virgin materials for new concrete products. Salvaged concrete is typically reused as coarse aggregate. A number of lifecycle studies have shown recycled aggregates to have an overall lower CO_2 footprint than virgin aggregates [62–64]. At high substitution rates, however, the use of recycle concrete for aggregates may increase the amount of cement needed to obtain the same compressive strength and workability of concrete made with virgin aggregates, thereby increasing the CO_2 footprint of the concrete product [21]. Optimal substitution rates vary in the literature depending on the performance metric of interest [65]. Whatever the substitution rate, the emissions benefit of recycled aggregates can be enhanced through investment in renewable sources of energy to power the recycling process, which involves breaking, removing, and crushing the salvaged concrete into smaller fragments with a specified size and quality.

Research suggests that recycled concrete may also be used as raw material for clinker production [1]. For this purpose, recycled concrete must be pulverized and treated to remove as much aggregate content as possible, leaving behind a cement paste that has high concentrations of lime (CaO) [66]. The cement paste could then be used as part of the feedstock to make clinker, thereby reducing CO_2 emissions from calcination, but cannot perfectly replace virgin materials because the right balance of calcium, silicon, aluminum, and ferric oxides must be maintained for correct clinker workability [67]. The environmental benefit of using pulverized concrete as a feedstock for clinker is not well documented, and ultimately depends on the CaO content of the pulverized concrete [66].

2.2.8. Carbon capture, utilization, and storage

If CO_2 emissions cannot be avoided, carbon capture and utilization (CCU) is one strategy for offsetting the emissions from concrete production. Several technologies have demonstrated the ability to utilize captured carbon as an input during the concrete production process. In one method that has been commercialized, cement made of low-lime calcium silicate minerals (e.g., Wollastonite) is cured with CO_2 instead of water in a special chamber that circulates CO_2 at atmospheric pressure, thereby accelerating the carbonation process that would occur with conventional concrete [1]. In an experimental method, hydrated lime ($Ca(OH)_2$) is exposed to liquid and supercritical CO_2 in a pressurized reactor (between 6 and 10 MPa), a technique that allows for the rapid absorption of CO_2 into the concrete mix [68]. In another experimental method, CO_2 is injected into the concrete mixer with freshly hydrating cement during the production of concrete blocks, eliminating the need for a specialized curing chamber, and reducing the amount CO_2 captured due to a shorter carbonation time [69]. In each method, the captured CO_2 was obtained from an industrial gas supplier or an offsite reservoir rather than onsite. Even if the waste CO_2 was captured onsite, creating a closed loop production process with zero CO_2 emissions is unlikely. To do so, all CO_2 lost during calcination must be regained through carbonation (the theoretical limit), or utilized for some other purpose, for which there is a very limited market.

Along with CCU, carbon capture and storage (CCS) is another method for preventing waste CO_2 from escaping into the atmosphere. This process consists of separating CO_2 from the flue gases released by industrial sources and transporting the collected CO_2 to permanent storage in secure locations such as deep saline aquifers and depleted oil and gas fields [70]. CCS has been demonstrated primarily in the context of power generation, but could feasibly be applied within the cement manufacturing sector, which emits higher concentrations of CO_2 gases compared to power plants [71]. The process of separating CO_2, however, requires energy, which may lead to even more emissions that must be sequestered. In the context of coal-fired power plants, for example, the energy lost to CCS (the energy penalty) ranges between 8 and 16% of the total energy produced onsite [72]. The energy penalty of CCS relative to CCU has not been well documented in concrete production. Any CO_2 reductions achieved through CCS, however, are vulnerable to leakage, which could seriously compromise the strategy's long-term potential for reducing GHG emissions [73]. The CO_2 reductions achieved through CCU, in contrast, are more stable, since the carbon is bound in the carbonate structure of the recycled concrete product.

3. Policy response

There is consensus on the need to curb GHG emissions. In 2015, 197 nations signed the Paris Agreement to prevent the most serious consequences of global climate change [74]. Each government is to pursue policies to significantly lower their carbon emissions. While the primary foci of climate regulations thus far have been reducing the use of fossil fuels through the energy industry, the large CO_2 footprint of the cement and concrete industry makes it a prime target for future regulation, especially as emissions reduction targets ratchet down.

At a basic level, there are two mechanisms by which government policy can reduce GHG emissions: 1) limit the activity that causes emissions by reducing output, or 2) limit the emissions intensity of the polluting activity. The menu of policy instruments available to governments to affect those outcomes is well defined in past literature. While terminology differs, policy instruments are generally categorized in the literature as command-and-control and market-based regulations [75–77]. Command-and-control regulations are direct government interventions in which firms are mandated to reduce emissions. In practice, these regulations target emissions abatement via standards. Market-based regulations are interventions where governments induce action indirectly, by modifying the incentives firms have to reduce emissions through pricing policies and incentive programs.

This section explores the impact these common environmental policy instruments may have on firms across the cement and concrete supply chain and on customers in the construction industry. We examine the effect of broadly applied carbon taxes and carbon cap-and-trade policies, which already regulate the cement industry in some cases. Also examined are a set of industry-specific regulations based on similar policies enacted in other sectors which include: technology and performance standards for cement and concrete producers and financial incentive programs that subsidize the use of technology or processes that produce less carbon-intense cement and concrete. In addition to instruments that are primarily focused on regulating the production and supply of concrete and cement, we also look at standards and incentives that may be leveraged in the construction sector; including unique non-financial incentive opportunities. Because these non-financial incentives are delivered through existing regulatory frameworks we refer to them as structural incentives.

The effects of the above policy interventions can ripple up and down the supply chain; however, practical application of policy levers may only be available at limited points on the supply chain. The supply chain begins with mineral extraction and ends with the delivery of concrete products to construction sites. Fig. 2 highlights the crucial nodes on the supply chain and indicates both the types of policies that are likely to directly impact market participants at that node, and summarizes the available GHG emissions abatement strategies at the specific production step. While Fig. 2 shows aggregates and transportation as nodes on the supply chain, they are sectors independent of the cement and concrete sector and therefore fall outside of this paper's assessment of policy instruments. The following sections explain each policy instrument and its effects on the industry supply chain in detail.

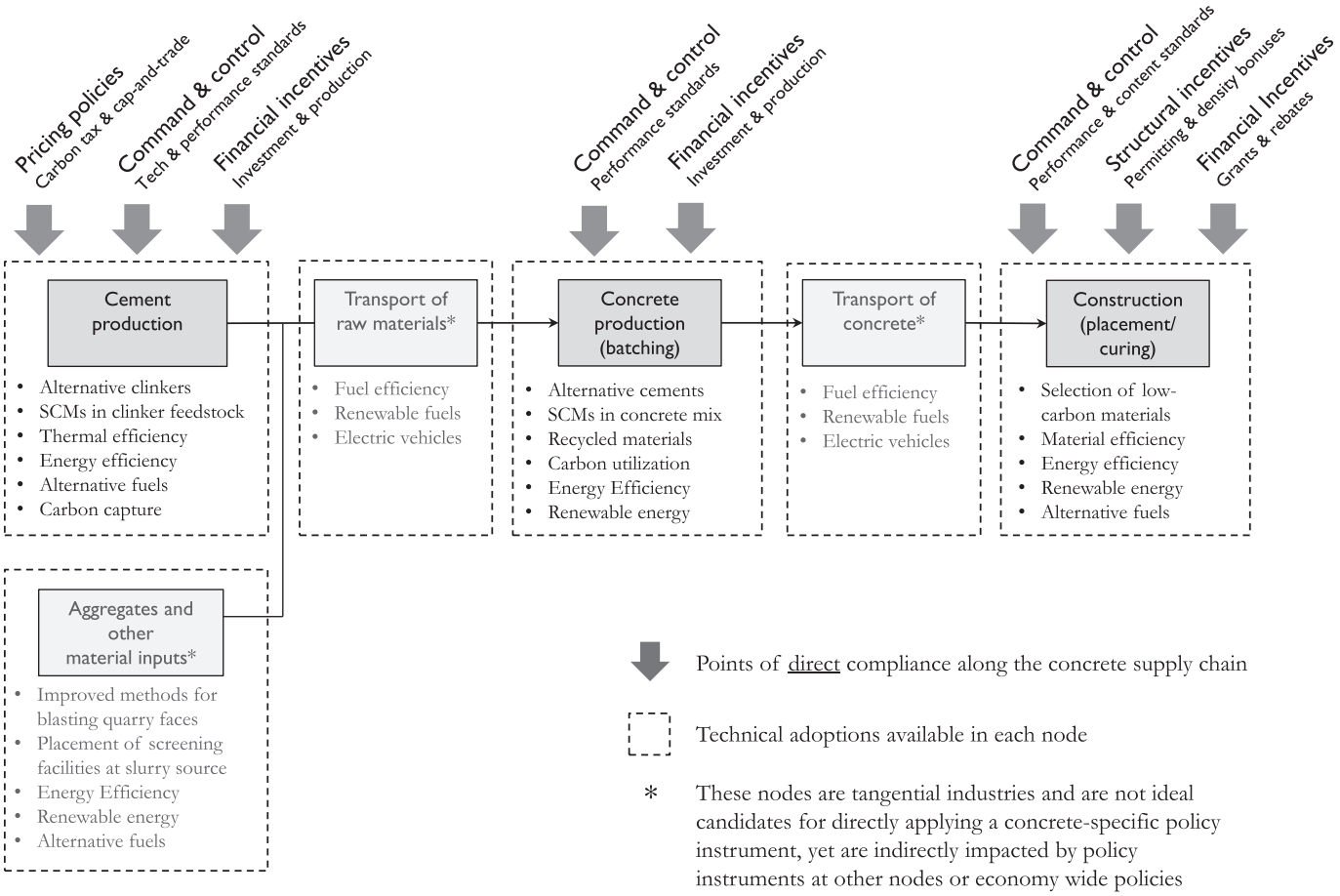

Fig. 2. The locations and effects of policy instruments along the concrete supply chain.

3.1. Pricing carbon: carbon taxes and cap-and-trade programs

Among the range of policy options designed to reduce carbon emissions, the most comprehensive in its impact on the concrete and cement supply chain is carbon pricing. Depending on design, carbon pricing regulations can impact both direct emissions from production as well as the cost of carbon-intensive inputs, such as transportation fuel or electricity. Regulators seeking to put a price on carbon emissions usually choose between one of two regulatory options; either carbon taxes or cap-and-trade programs [75]. In some jurisdictions these policies coexist, with each targeting different emissions sources. The two policies are administered differently and there are ongoing debates regarding their merits; however, both have the ultimate effect of putting a price on carbon emissions, meaning that all regulated firms under the system incur the same cost for each unit of GHG they emit [78].

3.1.1. Carbon taxes

Carbon taxes are the least complex method of pricing carbon. In theory, downstream taxes or fees can be levied on firms in relation to the mass of GHG they directly emit [78]. However, Metcalf and Weisbach [79] argue that upstream prices have the advantage of limiting the number of regulated parties while still creating a price signal for a significant portion of economy-wide carbon emissions. Consistent with their argument, real-world examples of carbon taxes are designed to price carbon emissions upstream of the emitter, levying taxes on the sales of energy commodities such as coal or petroleum, or secondary energy products such as electricity [80]. However, under a policy that only taxes energy commodities, CO_2 emissions from calcination—which can account for as much as 50% of cement production GHG emissions—avoid regulation.

While there are no present examples of downstream carbon taxes that directly regulate the cement and concrete industry, many jurisdictions have instituted carbon taxes on energy commodities that are key inputs to cement and concrete production. Table 1 identifies more than a dozen countries that have implemented carbon taxes since 1990. In some regions, these taxes exist alongside cap-and-trade programs limited to major emitters.

3.1.2. Cap-and-trade programs

Cap-and-trade programs, otherwise known as tradable permit systems or emissions trading systems (ETS), are policies in which regulators set a ceiling on total emissions allowed (the cap) and then establish a market where permits to emit GHG emissions can be bought and sold (the trade). While the methods of permit allocation, such as auctions or free allowances differ across cap-and-trade systems, a key feature is that once issued; permits are transferable and can be traded in the marketplace to regulated parties that need additional carbon emissions capacity [82]. However, regulated parties must retire (and not sell) one emission permit per ton of CO_2e they emit. Retiring a permit therefore represents a cost to manufacturers, either from the purchase of a permit or the lost opportunity of selling an unused permit.

In cap-and-trade systems, prices are set by the market and are contingent on regulated parties demand for the license to emit GHG emissions. Those who can reduce emissions can purchase fewer allowances if they are distributed by auction or sell unused allowances to other regulated parties if allowances are distributed freely. While the emissions price under a cap-and-trade program is not centrally set like carbon taxes, it exerts a similar influence on company behavior in the marketplace [78].

Most cap-and-trade program designs feature a progressively

Table 1
Carbon taxes that impact cement and concrete sectors.
World Bank [81]; Carl and Fedor [9].

Region	Tax Name	Year	Relevant Regulated Sectors
Finland	Finland Carbon Dioxide Tax	1990	Stationary Fuels, Transportation Fuels
Sweden	Sweden Carbon Dioxide Tax	1991	Stationary Fuels, Transportation Fuels
Norway	Norway Carbon Dioxide Tax	1991	Stationary Fuels, Transportation Fuels
Denmark	Denmark Carbon Dioxide Tax Act	1992	Electricity, Stationary Fuels, Transportation Fuels
British Columbia	British Columbia Carbon Tax Shift	2008	Electricity, Stationary Fuels, Transportation Fuels
Switzerland	Switzerland Carbon Dioxide Levy	2008	Stationary Fuels, Transportation Fuels
Iceland	Iceland Carbon Tax on Carbon of Fossil Origin	2010	Stationary Fuels, Transportation Fuels
Ireland	Ireland Natural Gas Carbon Tax, Mineral Oil Tax, and Solid Fuel Tax	2010	Transportation Fuels
Japan	Japan Tax for Climate Change Mitigation	2012	Electricity, Stationary Fuels, Transportation Fuels
France	France Domestic Consumption Tax on Energy Products	2013	Stationary and transportation fuels not covered by EU Emissions Trading System (ETS)
United Kingdom	Carbon Reduction Commitment	2013	Electricity
Mexico	Mexico Special Tax on Production and Services	2014	Stationary Fuels, Transportation Fuels

declining GHG emissions cap, creating pressure on industry to commit to ever deeper emissions cuts. As a matter of administrative practicality, cap-and-trade regulations typically limit the number of directly regulated entities to “large” emitters. For example, under California's policy, only entities that emit GHG in excess of 25,000 metric tons are directly regulated [83].

As shown in Table 2 there are currently seven national, subnational, or regional governments that operate cap-and-trade programs affecting the costs of cement and concrete production. These programs include modest-sized cement markets such as those in the European Union, California, and Chinese provincial pilots. The Chinese provincial pilot cap-and-trade programs are tests for a country-wide program which when operational will cover the largest cement and concrete market in the world. Six of the cap-and-trade programs in operation include emissions from cement manufactures under the program cap. In contrast, the Regional Greenhouse Gas Initiative in the U.S., regulates only electricity, a key input in cement and concrete production.

3.1.3. Firm compliance requirements

Fig. 2 above shows both carbon taxes and cap-and-trade acting directly only on the cement industry because direct emissions from other nodes are comparatively insubstantial. Under typical pricing designs, cement producers are likely to be the only firms regulated directly by a cap-and-trade system or downstream carbon tax policies. Under those regimes, cement producers would be required to both track and report their GHG emissions and either pay a tax or hold and retire compliance permits for GHGs that they emit. Carbon pricing instruments implemented upstream on energy commodities or electricity will not impose additional regulations on the cement and concrete market directly. However, because energy is a primary input in all stages of the supply chain, each node will face those embedded costs in the energy products they purchase.

3.1.4. Effect of carbon pricing on the concrete and cement market

In principle, carbon pricing will reduce GHG emissions from the cement and concrete industry by suppressing demand (and therefore production) with higher product prices and by creating an incentive for firms to reduce the GHG intensity of production. Increased costs of cement production stemming from the purchase of a GHG allowance, the impact of carbon taxes on energy inputs, and the employment of GHG emission abatement measures will result in higher market prices for cement and concrete. Empirical analysis of the cost pass-through of GHG prices conducted by Miller et al. [84] estimates that 11% of a GHG emissions price will be borne by producers while the rest of the cost would be passed on to consumers. Economic theory suggests that higher prices for a good will decrease its demand, as buyers decide to purchase less of the product or seek substitutes.

Fig. 3 shows how pricing regulations impact regulated industries, and how the impact of increased prices for cement and energy inputs flow downstream through the supply chain to concrete producers who either pass along the cost increase to customers, or if possible, purchase low-carbon cement from competing suppliers. Further downstream, construction firms or other cement and concrete users facing a higher price may choose to employ material use conservation strategies, substitute to other building materials, or reduce output altogether. However, cement and concrete purchases are a relatively small portion of overall construction costs. Rootzen and Johnsson [85] found that even if carbon pricing doubled the cost of cement, the cost of a residential building will only increase by one percent. Therefore, construction firms might be insensitive to increases in costs—even if carbon prices are very high—and may simply absorb small cost increases without changing purchasing behavior. This will be especially true if alternatives to material conservation require a more expensive input, such as labor [86].

Furthermore, most national and subnational carbon pricing policies are examples of incomplete regulation because they apply to cement producers in the regulated jurisdiction but not to those outside the jurisdiction who can import lower cost, but higher-carbon intensive, cement into the regulated jurisdiction's market. The resulting price differentials between imported and domestic products may lead to

Table 2
Cap-and-trade programs that impact cement and concrete sectors.
Carl and Fedor [9].

Region	Program Name	Year	Regulated Sectors
European Union	European Union ETS	2005	Cement Manufacturing, Electricity
Switzerland	Swiss ETS	2008	Cement Manufacturing
Northeastern U.S.	Regional Greenhouse Gas Initiative	2009	Electricity
California, U.S.	California Cap-and-Trade Program	2013	Cement Manufacturing, Electricity, Transportation Fuel
Quebec, Canada	Quebec Cap-and-Trade System for Emission Allowances	2013	Cement Manufacturing, Electricity, Transportation Fuel
China	Provincial ETS Pilots	2014	Cement Manufacturing, Electricity
South Korea	Korean ETS	2015	Cement Manufacturing, Electricity, Transportation Fuel

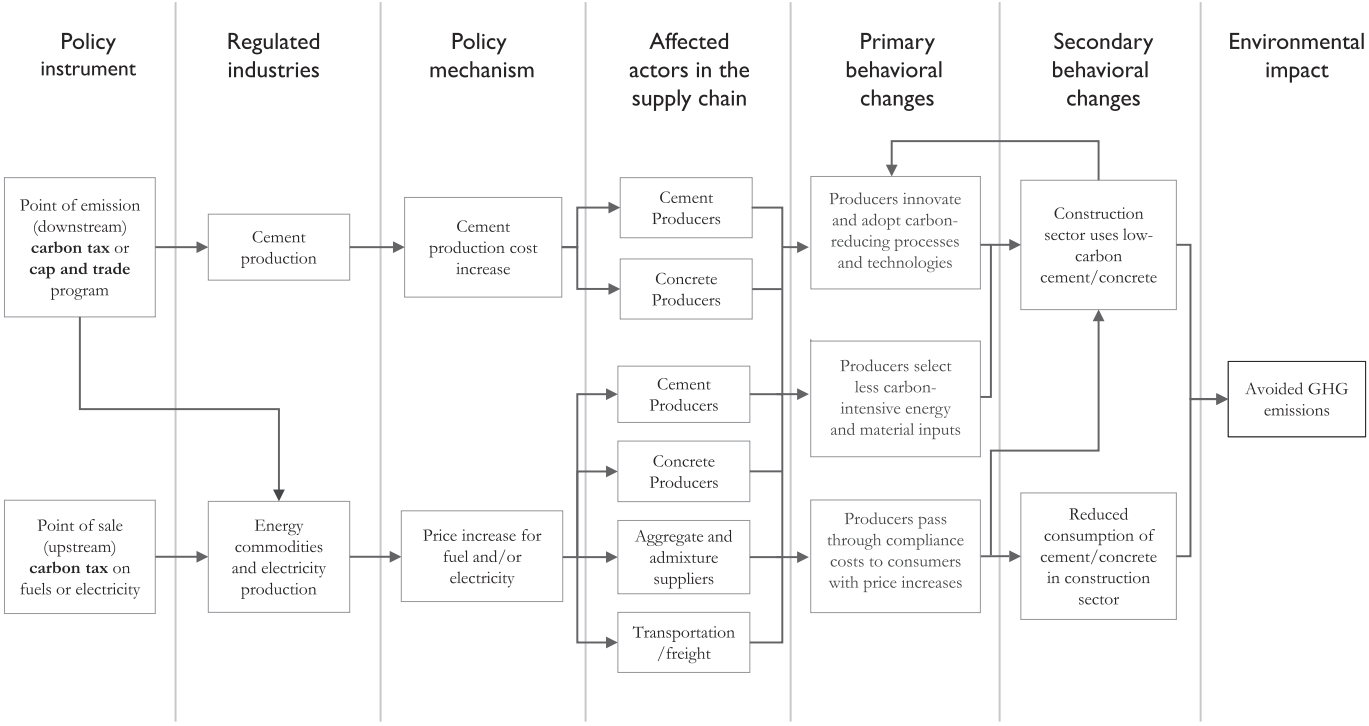
Policy instrument
Regulated industries
Policy mechanism
Affected actors in the supply chain
Primary behavioral changes
Secondary behavioral changes
Environmental impact
Point of emission (downstream) carbon tax or cap and trade program
Cement production
Cement production cost increase
Cement Producers
Concrete Producers
Producers innovate and adopt carbon-reducing processes and technologies
Construction sector uses low-carbon cement/concrete
Cement Producers
Concrete Producers
Producers select less carbon-intensive energy and material inputs
Avoided GHG emissions
Point of sale (upstream) carbon tax on fuels or electricity
Energy commodities and electricity production
Price increase for fuel and/or electricity
Aggregate and admixture suppliers
Transportation /freight
Producers pass through compliance costs to consumers with price increases
Reduced consumption of cement/concrete in construction sector

Fig. 3. Logic model for carbon pricing instruments.

increased purchases of imported higher-carbon cement. This results in GHG "leakage" because the emissions simply shift to another location or sector where they are uncontrolled or uncounted. For example, Smale et al. [87] and Ponssard and Walker [88] suggest that the European Union ETS may be causing leakage into the European cement market raising concerns as other jurisdictions begin adopting carbon pricing instruments.

Designing carbon pricing policies that curb GHG emissions while simultaneously protecting the competitive position of the emissions-intensive domestic cement industry requires a detailed knowledge of the structure and dynamics of the industry. Fowlie et al. [89] conducted the most recent empirical analysis of the design of market-based emissions policy alternatives for the cement industry to date for the U.S. They evaluated four market-based emission policy designs: 1) carbon taxes which are equivalent to permit auctioning; 2) grandfathering permits or giving free permits based on historical emissions; 3) dynamic allocation updating or allocating permits based on emissions from the last compliance period; and 4) border tax adjustments (BTA) which penalize imports according to their average carbon content.

The authors find that alternative design attractiveness depends upon the assumed SCC. When the SCC is below $40 per ton of CO_2 all four policies reduce social welfare. Social welfare losses occurred under the carbon tax/permit auction policy because firms bore the full cost of compliance. However, once the SCC rose to about $40, Fowlie et al. [89] found that the policy design involving dynamic allocation updating and BTA regimes become welfare improving. The BTA regime outperforms dynamic allocation updating at high-carbon values because taxing imports more effectively mitigate emissions leakage and improves domestic terms of trade. Permit grandfathering policies result in welfare losses up until the SCC exceed $60 per ton of CO_2e.

In addition to influencing the quantity of cement produced, in principle, carbon prices will incentivize producers to reduce the carbon intensity of their production process. Under the condition of perfect competition firms that find ways to reduce production costs will pass along those savings to purchasers to compete with rivals on price. To minimize the production cost of GHG pricing regulations, firms would pursue strategies that reduce regulated emissions at a cost less than that of the carbon price. However, because the cement industry is heavily concentrated and firms have significant market power, they do not behave like firms do under perfect competition and may not respond by price minimizing.

Whether the use of carbon pricing regulations in concentrated industries exacerbates the exercise of market power within domestic cement markets is the subject of continued debate. Buchanan [90] originally argued that first-best policies such as carbon taxes or cap-and-trade should only be used in a competitive market and not in a concentrated industry such as cement. He explained that concentrated industries like cement have a marginal incentive to reduce output to increase prices and thus profits. Therefore, those concentrated industries already produce below the socially optimal output and emission regulation would unduly further reduce their output levels. Oates and Strassmann [91] counter argued that the welfare gains from reducing pollution would likely offset any welfare losses associated with reduced industry output.

3.2. Command-and-control policies: direct regulation of GHG emissions

Command-and-control regulations directly target emission reductions from specific industries by requiring them to meet centrally set standards. They have been the conventional approach of environmental policy for many years. While there are no present-day examples of these instruments used specifically to limit GHG emissions in the cement and concrete industries, command-and-control policies have been used extensively in the past to regulate environmental externalities in other industries. Therefore, we expect that such policies will also be considered for concrete and cement industries. Command-and-control instruments are commonly classified as either technology or performance standards. The former is when a specific control technology is prescribed by a regulator. The latter is when regulators require firms to meet a defined performance metric [75,76]. In the following sections, we describe the effect on the concrete supply chain caused by a production-based technology standard and three different performance-based standards: 1) production GHG intensity standards, 2) low-carbon concrete use standards, and 3) low-carbon content standards.

3.2.1. Technology and performance standards in production

Emissions technology standards and emissions intensity standards for production are similar in that they are centrally set and enforced and are designed to limit the emissions intensity of specific production processes. Where the two standards differ is in the flexibility by which regulated entities can meet GHG emissions reductions [92]. Technology standards mandate the use of a specific technology. Conversely, performance standards set a metric that must be achieved, letting individual firms choose their own least-cost compliance pathway.

Compared to performance standards, technology standards are relatively simple in design. In principle, a regulator implementing such a standard could mandate the use of any carbon-reducing technology. While it is possible that technology mandates could be implemented at any point of the production supply chain, they are most feasible in cement production where mandated fuel switching or technology improvements could yield significant GHG emissions reductions. Most examples of technology standards are focused on air quality and mandate “end-of-pipe” solutions, such as catalytic converters or other post-combustion solutions to air pollution. To date, end-of-pipe GHG emissions control technology have been economically infeasible. However, as CCS technology matures, mandated use of such technologies may become an option.

Emissions intensity standards can be as simple as limits on emissions per unit of output, such as per-mile emissions limits for vehicles. More complex policy designs can include GHG emissions intensity of inputs to measure lifecycle emissions intensity, or flexible market mechanisms which allow over-complying firms to sell compliance credits to under-complying firms. Many jurisdictions have adopted low-carbon fuel standards that incorporates both design features to regulate the carbon intensity of transportation fuels [93]. A lifecycle-based approach would be a particularly useful way to regulate the carbon-intensity of concrete products because concrete manufactures have flexibility in input selection and the majority of GHG emissions embodied in concrete are embedded in inputs and not as a direct result of the concrete batching process.

While there are no standards in place for GHG emissions in the cement and concrete sector, several jurisdictions have passed carbon intensity standards for transportation fuels, which are a small but important input in the supply chain. Examples of these policies are presented in Table 3 below.

3.2.2. Technology and performance standards in construction

In most locations, the construction industry is highly regulated through building codes, which are collections of technology and performance standards. Many jurisdictions have adopted green building codes which are designed to improve the environmental performance of buildings [96]. Jurisdictions interested in decreasing the GHG emissions impact of concrete in downstream uses can write standards into their building codes mandating the use of particular types of low-carbon cement or one that meets a specific carbon intensity standard. The authors are unaware of any rules or codes that require the use of low carbon cement. Table 4 provides examples of model building codes that have been developed for regulating agencies to adopt in their jurisdiction.

3.2.3. Content standards in production and construction

Content standards share similarities with intensity standard policy instrument. However, instead of mandating adherence to a specific performance standard for all materials, content standards require a specified percentage of a product meet a standard. For example, renewable portfolio standards require electricity providers to procure a minimum percentage of their electricity from renewable sources, creating a floor on demand for clean energy resources [98]. A similar content standard could be applied to construction firms, requiring a portion of the concrete or cement they use to be green, creating a guaranteed market for those materials. Content standards may also be implemented more narrowly. Recycled material content standards which require a minimum content of secondary materials in produced goods have been employed in a few jurisdictions as a method to divert waste from disposal [99]. Similar content standards targeting GHG emission reductions through minimum contents of recycled aggregate, clinker substitutes, or alternative cements could be employed for concrete production. However, because the use of materials impacts the material properties of concrete, such standards may not be feasible.

3.2.4. Firm compliance requirements

Fig. 2, above, illustrates how command-and-control policy instruments can be applied at each node of the cement and concrete supply chain. Technology standards levied on cement producers would simply require firms to purchase and implement the specified technology in their production process. Intensity standards that only regulate direct

Table 3
Standards that impact GHG emissions in cement and concrete production.
Chalmers and Archer [94]; Yeh et al. [95].

Region	Guideline Name	Year	Description
United Kingdom	Renewable Transport Fuel Obligation	2008	Requires an increasing fraction of biofuel blended into supplied transportation fuels.
British Columbia, Canada	Renewable and Low Carbon Fuel Requirements	2008	A declining standard on allowable lifecycle carbon emissions from transportation fuels.
California, U.S.	Low Carbon Fuel Standard	2009	A declining standard on allowable lifecycle carbon emissions from transportation fuels.
Oregon, U.S.	Oregon Clean Fuels Program	2009	A declining standard on allowable lifecycle carbon emissions from transportation fuels.
European Union	EU Low Carbon Fuel Standard	2009	A declining standard on allowable lifecycle carbon emissions from transportation fuels.

Table 4
Model building codes that impact cement and concrete sectors.
GSA [96]; Subasic [97].

Region	Name of code	Year	Description
U.S.	Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings (ASHRAE 189.1)	2009	Designed as a model building code that can be adopted by multiple jurisdictions. Requires either 1) a 5% improvement in the lifecycle impact of the building on at least two impact measures, as compared to two reference designs, or 2) the use of building materials that meet certain content standards.
Global	International Green Construction Code (IGCC)	2012	Designed as a model building code that can be adopted by multiple jurisdictions. Requires either 1) a 20% improvement in the lifecycle impact of the building on global warming and at least two other impact measures, as compared to a reference design, or 2) at least 55% of the building materials (calculated by mass, volume or cost) meet certain content standards.

emissions would require firms to report emissions and output to verify compliance. On the other hand, a lifecycle-based intensity standard on concrete products would require carbon-intensity measurements for all inputs including cementitious materials, aggregates, and other admixtures. A low-carbon concrete product standard or green concrete content standard targeted towards construction firms would require producers who wish to sell in that market to certify that their products are sufficiently low-carbon and force construction firms to track and report the carbon intensity or content performance of the concrete used in their projects.

3.2.5. Effect of command-and-control regulation on the concrete and cement market

By way of design, command-and-control regulations are directed at reducing the carbon-intensity of cement and concrete production. Under technology or GHG emissions intensity standards, regulated firms are forced to reduce the GHG intensity of production. Firms will respond either by installing technologies that reduce or capture emissions or, if permissible, by pursuing other, lower cost abatement options, such as switching fuels and material inputs. The amount of choice firms have to on how to implement carbon reduction strategies depends on the flexibility of the policy instrument used.

In a downstream regulation scenario, such as building codes, requirements to purchase low-carbon concrete either through a performance or content standard create demand for those products. A standard under which all buyers within the market must purchase low-carbon cement is functionally equivalent to production GHG emissions intensity regulation because both policies have the effect of requiring cement or concrete to meet a defined GHG emissions intensity to be marketable. A content standard or a downstream performance standard that does not affect the entire product market will not necessarily incentivize all producers to create low-carbon products, but it ensures some low-carbon products be sold creating a floor for demand.

Command-and-control regulations may affect the quantity of cement demanded when those regulations increase the price of cement and concrete production and those costs are passed on to consumers. Goulder and Parry [75] argue that these policies are less than optimal because they do not sufficiently reduce GHG emissions by suppressing consumption. To achieve similar emission reductions to price-based policy instruments, regulators must put more stringent GHG emissions intensity constraints on producers than they would choose to pursue under a pricing instrument where the cost of emissions can be passed on to consumers directly. On the other hand, because the cement industry is concentrated and firms have an incentive to reduce output to increase prices, output may already be low enough that suppressing consumption could lead to a welfare-reducing outcome [90]. Furthermore, Holland [100] argues that GHG emissions intensity standards combined with consumption taxes may be welfare-improving relative to GHG emissions pricing in the presence of either market power or leakage.

Fig. 4 shows how standards affect decisions made by firms in cement and concrete production and the construction sector and how those effects influence decisions elsewhere in the supply chain.

3.3. Financial and structural incentives

Unlike command-and-control policies, which obligate low-carbon intensity production or use of low-carbon concrete, incentive programs promote voluntary adoption of those processes and products by offering benefits to those who choose to use them. In this section, we describe impacts on the concrete supply chain caused by (1) financial incentives for the production or consumption of low-carbon cement and concrete and (2) structural incentives that provide valuable non-financial benefits for low-carbon cement use.

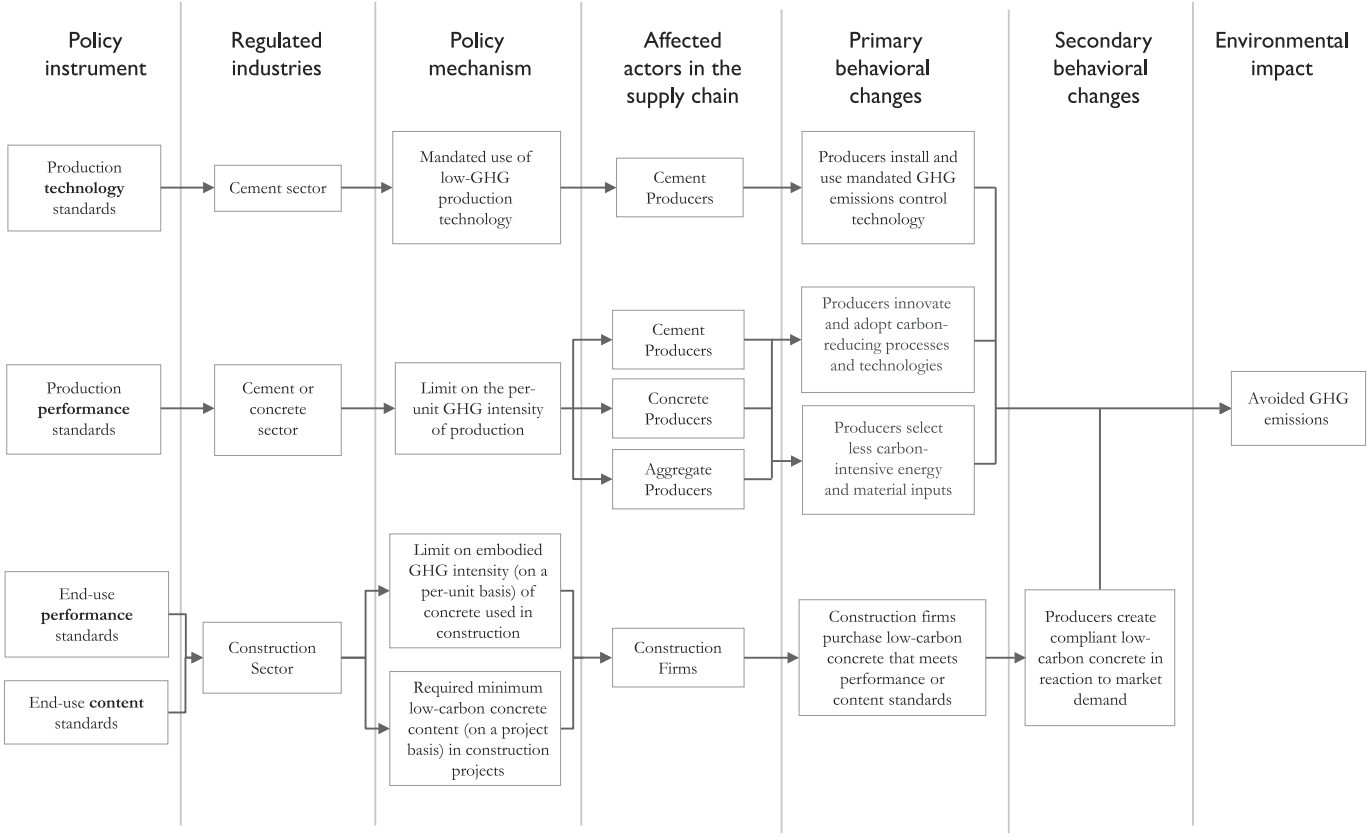
Policy instrument
Regulated industries
Policy mechanism
Affected actors in the supply chain
Primary behavioral changes
Secondary behavioral changes
Environmental impact
Production technology standards
Cement sector
Mandated use of low-GHG production technology
Cement Producers
Producers install and use mandated GHG emissions control technology
Production performance standards
Cement or concrete sector
Limit on the per-unit GHG intensity of production
Cement Producers
Concrete Producers
Aggregate Producers
Producers innovate and adopt carbon-reducing processes and technologies
Producers select less carbon-intensive energy and material inputs
Avoided GHG emissions
End-use performance standards
End-use content standards
Construction Sector
Limit on embodied GHG intensity (on a per-unit basis) of concrete used in construction
Required minimum low-carbon concrete content (on a project basis) in construction projects
Construction Firms
Construction firms purchase low-carbon concrete that meets performance or content standards
Producers create compliant low-carbon concrete in reaction to market demand

Fig. 4. Logic model for performance-based standards.

Table 5
Financial incentive programs that impact cement and concrete sector.
USGBC [102].

Incentive Type	Description
Tax Credits and Abatements	Reduces producer's or consumer's tax obligation for the production or use of low-carbon products.
Fee Reductions or Waivers	Reduces construction-related permitting costs for developers or contract who incorporate low-carbon building materials into building design.
Grants	Rewards developers who commit to using low-carbon building materials with partial funding of their project.
Loan Assistance	Provides low interest loans to developers who incorporate low carbon building materials into their building design.

3.3.1. Financial incentives

Financial incentives (otherwise known as subsidies) for low-carbon cement and concrete could take the form of tax credits, sales tax exemptions, loan assistance, rebates or grants available to those who produce or purchase low-carbon concrete products. Regulators decide on an appropriate incentive rate and whether the incentive goes to the consumer or the producer. Currently there are no incentive programs that target the cement and concrete industry specifically. However, some technology and process-based incentives are in place that could be claimed by cement manufacturers. For example, firms in the U.S. that employ CCS technology may be eligible for tax credits based on the mass of CO2 they sequester [101]. Table 5 describes how these incentives could be applied to the production or purchase of building materials to encourage the use of low-carbon concrete products.

3.3.2. Structural incentives

Structural incentives would be novel, non-financial incentive options for reducing the GHG intensity of concrete used in construction projects (See Table 6). These incentives would only be available in jurisdictions where the downstream industry of cement and concrete (i.e. construction) is heavily regulated. To start a construction project, builders are often required to submit to permitting processes that can take significant amounts of time and money to complete. Government agencies can offer expedited permitting processes, and therefore reduce project costs for those projects that utilize low-carbon concrete. Additionally, local land use ordinances often set limits on the allowed unit density of building projects. Government agencies can relax those limits for projects that utilize low-carbon concrete, which can significantly increase the value of the final construction project.

There are currently no structural incentive programs that specifically incentivize carbon emissions reductions in the concrete and cement sectors. Still, many jurisdictions have adopted programs that reward developers for complying with the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) building standards, which provide elective credits for the use of low-impact building materials, but do not require their use [103].

3.3.3. Firm compliance requirements

As indicated in Fig. 2, above, incentives can be an effective policy tool to encourage cement and concrete producers and consumers to reduce GHG emissions. Because incentives are voluntary, there are no direct compliance requirements for any firm. However, concrete or cement consumers seeking to take advantage of incentives will be required to demonstrate eligibility. Likewise, producers who wish to take advantage of incentive-driven demand for low-carbon products will have to certify those products as incentive-eligible. However, because these measures are voluntary, firms will only pursue them if the benefits outweigh the costs.

3.3.4. Effect of incentives on the concrete and cement market

Incentive policies to use or produce lower-carbon cement will only affect GHG emissions by reducing the emissions intensity of cement or concrete production. Because incentive-driven GHG emissions reductions are voluntary, they will not occur if they increase the cost of production. This means that unlike other policies, incentives will not increase the price of nor suppress demand for concrete or cement, yielding no GHG emissions reductions from diminished production.

Fig. 5 illustrates how incentives impact the decisions of cement and concrete producers and consumers. Unlike binding standards, incentives do not preclude the sale of high-carbon products. However, if the value of the production incentives negates increases in production costs, producers are incentivized to switch from high-to low-carbon production processes and consumers can purchase low-carbon cement at a potentially lower cost. Similarly, if financial or structural incentives increase the demand for low-carbon cement and concrete, suppliers are incentivized to produce it in greater quantities, replacing high-carbon concrete.

Insofar as producers or consumers place a value on environmental stewardship, incentive programs may offset costs enough to justify the purchase or production of low-carbon cement and concrete for its green attributes, even if the cost increase is not fully covered. However, if the incentive recipient's decision to purchase low-carbon cement or concrete is not dependent on the value of the subsidy, but they receive one anyway, they become a free rider, reducing the efficiency of the incentive program. Such free-ridership problems have been observed in other cases of incentive use, most notably among them in energy efficiency programs [104].

4. Evaluation of policy instruments

The policy instruments discussed in this paper have contrasting strengths and weaknesses. This section describes the merits of one policy instrument over another according to four criteria: 1) cost-effectiveness, 2) control over emission reductions, 3) technological innovation, and 4) revenue generation or requirements. Table 7 presents the advantages and disadvantages of the policies that we assess.

Table 6
Structural incentive programs that impact cement and concrete sectors.
USGBC [102].

Incentive Type	Description
Expedited Review/Permitting Processes	Reduces the duration of the review and permitting process for construction projects that use low-carbon building materials, reducing developer costs.
Density Bonuses	Rewards developers that use low-carbon building materials with an increase in Floor Area Ratio (FAR) or other measures of density (e.g., height allowances), which ultimately enhances the project's profitability through the sale and/or rental of additional units.

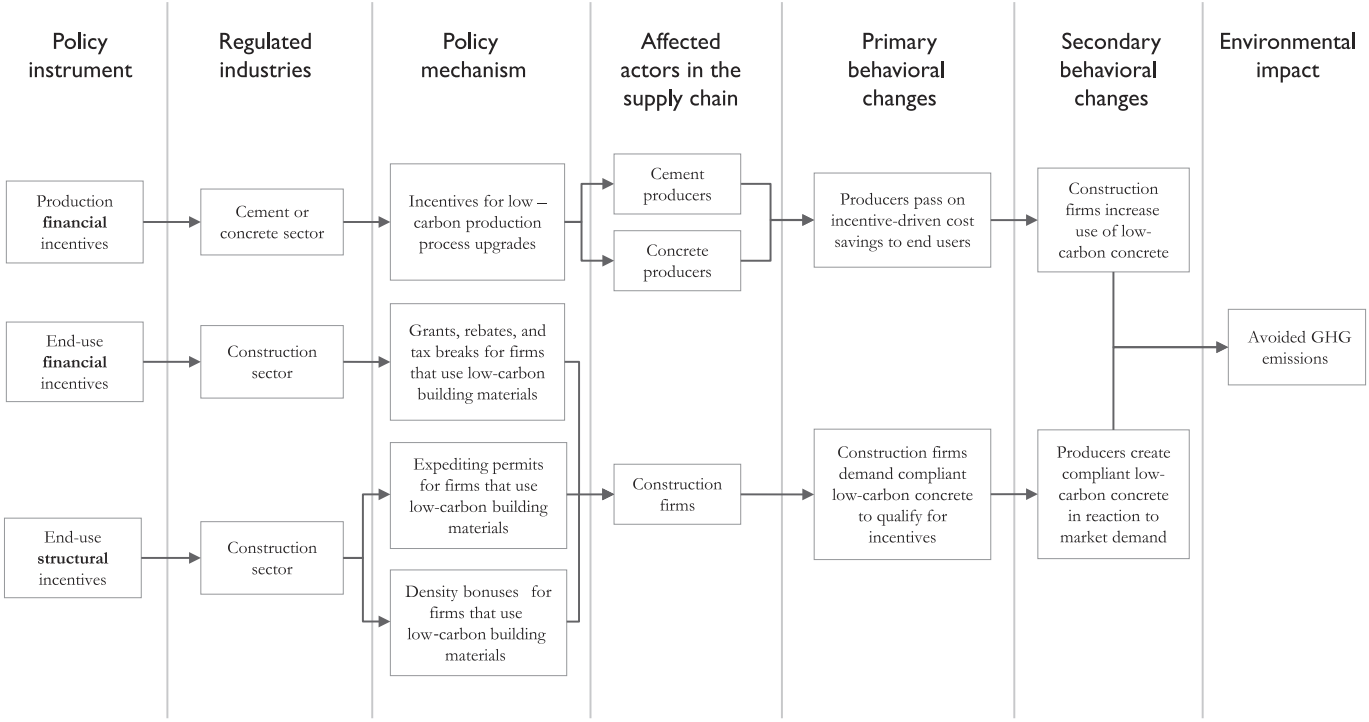
Policy instrument
Regulated industries
Policy mechanism
Affected actors in the supply chain
Primary behavioral changes
Secondary behavioral changes
Environmental impact
Production financial incentives
End-use financial incentives
End-use structural incentives
Cement or concrete sector
Construction sector
Construction sector
Incentives for low – carbon production process upgrades
Grants, rebates, and tax breaks for firms that use low-carbon building materials
Expediting permits for firms that use low-carbon building materials
Density bonuses for firms that use low-carbon building materials
Cement producers
Concrete producers
Construction firms
Producers pass on incentive-driven cost savings to end users
Construction firms demand compliant low-carbon concrete to qualify for incentives
Construction firms increase use of low-carbon concrete
Producers create compliant low-carbon concrete in reaction to market demand
Avoided GHG emissions

Fig. 5. Logic model for financial and structural incentives.

4.1. Cost-effectiveness

Policies that are more cost-effective accomplish a unit reduction in emissions at lower social costs. Carbon taxes or cap-and-trade programs can be the most cost-effective policy instruments for regulating GHG emissions from concrete production. In other words, these policies can achieve a targeted level emissions reduction at the lowest possible combined costs to society [75]. What makes them so cost-effective is that they send price signals to communicate the SCC throughout the supply chain; to material suppliers, concrete manufacturers, building designers, building owners, and others. These price signals induce those firms within the supply chain with the lowest cost of abatement to abate more GHG emissions relative to firms with higher abatement costs [92]. Furthermore, cap-and-trade programs that span multiple industries provides a price signal that incentivizes firms with low abatement costs in any industry to reduce more GHG emissions relative to other firms. If firms in other sectors can exploit abatement pathways that are inexpensive, demand for GHG emissions allowances diminishes, causing market prices to decrease which will impact the pay-or-abate decisions of concrete or cement producers. Each firm is free to decide how much to reduce their carbon throughput and how much extra to pay for their remaining carbon output through taxes or allowance expenditures.

In contrast, in perfectly competitive markets standards and financial incentives are less cost-effective because they change the incentives for

Table 7
Advantages and disadvantages of policy instruments for reducing emissions from concrete.

Policy Instrument	Advantages	Disadvantages
Carbon Tax: *tax based on emissions quantity.*	● Cost-effective ● Revenue generating ● Drives technological innovation	● Uncertain impact on emissions relative to cap-and-trade ● Risks leakage in open markets ● Risks exacerbating suppression of supply in concentrated industries
Cap and Trade: *tradable carbon allowances between industrial sectors.*	● Cost-effective ● Control over emissions ● Drives technological innovation ● Revenue generating	● Risks leakage in open markets ● Risks exacerbating suppression of supply in concentrated industries
Technology Standards: *Mandated technology use*	● Forces the adoption of carbon-reducing technologies ● Simple enforcement and compliance	● Limits emissions reductions to a single process ● No compliance flexibility ● Very weak driver of innovation ● Uncertain impact on emissions
Performance Standards: *Mandated low-carbon intensity of cement and concrete products*	● Allows for flexible compliance relative to technology standards ● Simple enforcement and compliance	● Narrowly targets carbon emissions ● Low compliance flexibility ● Weak driver of innovation ● Uncertain impact on emissions
Financial Incentives: *subsidies for low-carbon building materials purchase or production.*	● Effective for commercializing experimental technologies ● High visibility to consumers	● High revenue requirements ● Can lead to free-riders
Structural Incentives: *non-financial incentives for use of low-carbon building materials.*	● Minimal revenue requirements ● Easy to implement	● Weak driver of innovation ● Limited impact on emission reductions

emissions of only one or a subset of entities within a supply chain rather than for all. For example, if a low-carbon concrete standard was imposed on producers, it would not signal to building or infrastructure designers and property owners to reduce their carbon intensity although they may have a lower cost of abatement, nor will it incentivize firms in other unregulated industries to reduce their carbon output even if they can do so more efficiently than cement or concrete producers [78]. Similarly, a financial incentive policy for the use of low-carbon concrete by building and infrastructure designers might reduce the cost disadvantage between low-carbon and conventional concrete. However, it will not incentivize the producers of conventional concrete to search for cost-effective ways to reduce their carbon intensity at the lowest possible cost. The potential for free riders in incentive programs further limits the cost-efficiency of incentive programs.

4.2. Control over emissions reduction

The ability of these policies to deliver targeted emissions reduction with certainty varies. Carbon cap-and-trade programs offer the greatest *ex ante* policy control over total CO_2 emissions because the cap effectively limits total allowances and thus total emissions with certainty. Many cap-and-trade programs progressively reduce the size of the cap or the number of allowances in subsequent years.

However, once carbon is priced, concrete or cement consumers may face an incentive to avoid the added cost of materials by importing unregulated materials from jurisdictions that do not have cap-and-trade or carbon tax policies. Smale et al. [87] and Ponssard and Walker [88] suggest that the EU ETS could lead to significant leakage. While leakage will reduce the emissions reduction effectiveness of pricing policies, policymakers may attempt to fix those problems by developing importation regulations, such as border tax adjustment. They may also consider permit allocation policies that assign free permits to cement producers based on specific output criteria [105,106].

Responding to these concerns, Fowlie, et al. [89] found that once the SCC rose to about $40, policy designs involving dynamic allocation updating and border tax adjustment regimes become welfare improving. The border tax adjustment regime outperforms dynamic updating at high-carbon values because the tax on imports more effectively mitigates emissions leakage and improves domestic terms of trade. The failure to compensate for imports can lead to leakage and an associated increase in GHG emissions outside of the regulated jurisdiction and potentially a net increase in emissions overall if the imported cement has a higher-than-average carbon intensity. While a border tax may be an effective method to avoid leakage, it should be noted that any border tax would have to be carefully designed in order to avoid violation of international trade treaties [107].

Carbon taxes and performance standards reduce CO_2 emissions as a function of the stringency with which they are set. Higher taxes per ton of carbon or lower CO_2 intensity standards for cement or buildings will lower the emissions released by firms. However, at any given level of policy stringency, the actual amount of emissions released varies with changes in the profitability (e.g., price) of cement or concrete, total market sizes, and the costs of CO_2 abatement. If the price of cement is rising or the size of the market is expanding, ceterius paribus, emissions are likely to increase. In contrast, when employing taxes or performance standards if there are innovations in CO_2 abatement technologies, making them more effective and cheaper to deploy, then firms will abate more CO_2 and total emissions are reduced.

Financial and structural incentives for the adoption and use of innovative low-carbon cement are likely to have the least effect on emissions reduction in the short-term. This is because although financial incentives lowers costs to adopters and induce the scaling of the market for low-carbon cement, these policies do not change the incentives for conventional producers and consumers of cement to reduce emissions.

4.3. Technological innovation

These policies also vary in the market incentives that they create for firms to innovate toward low-carbon cement, concrete, transportation fuels, and related abatement technologies. Policies that price carbon create the broadest set of incentives for innovation throughout the supply chain. The price premium on lower-carbon cement rewards innovators with immediate cost savings as they move toward lower-carbon intensity technologies, fuels, and other production inputs. Carbon pricing mechanisms are also best positioned to drive innovation and research and development for less-developed very low-carbon cement and concrete pathways, such as solar-thermal conversion of calcium carbonates to calcium oxides and advanced CCU technology, because they provide incentives to reduce carbon above and beyond what the current best-available technologies provide.

In current practice, carbon taxes are assessed on fossil fuel emissions only, and are typically assessed at the point of sale. Those taxes create incentives for firms to pursue energy-related emissions reductions strategies such as switching to lower-carbon or renewable fuels/energy and making energy-efficiency upgrades to equipment. However, fuel-based carbon taxes provide weaker incentives for clinker-substitution strategies, which can provide some energy-related benefits but primarily reduce process emissions. Furthermore, fuel-based carbon taxes provide no incentive for firms to recycle concrete as aggregates or employ CCS or CCU technology to capture cement process emissions. To incentivize reductions in process emissions, an additional complementary policy (such as tax-credits) is needed to create a monetary benefit for reducing process emissions. In cap-and-trade systems, process emissions are captured by the same instrument as energy emissions, therefore incentivizing all abatement strategies equally.

Economists have long suggested that command-and-control regulations are less effective at spurring innovation than market-based policies [108]. Regulations such as performance or technology standards “pull up” firms that would otherwise lag in implementing existing technologies, but they lack the continuous incentive mechanism offered by carbon prices to induce producers to go beyond what is required. As a result, firms along the concrete supply chain are not rewarded for going above and beyond regulations. Thus, firms will meet their regulatory obligations but are unlikely to make investments in new emission-reducing technologies. Empirical studies by Burtraw et al. [109] and Isaksson [110], which analyzed sulfur dioxide markets in the U.S. and a charge on oxides of nitrogen in Sweden, found that pricing policies enhanced technological advancement and decreased costs relative to command-and-control regulations.

Current practices for technology standards in air pollution regulatory regimes require that firms use a regulator-defined best available control technology equipment. An analogous technology standard for controlling GHG emissions could, for example, require firms to employ best-available energy-efficient equipment such as dry-process kilns, or install end-of-pipe CCS solutions. However, a standard focused on those technological pathways would not provide incentives to switch fuels, substitute clinker, or use CCU processes. Alternatively, technologically agnostic performance standards that simply set GHG emissions intensity limits provide an incentive for producers to flexibly pursue whatever control technology or abatement strategy that is most cost-effective for their operations, potentially allowing for innovations that would not otherwise be considered.

4.4. Revenue generation or revenue requirements

Policies may vary in whether they generate or require public revenue, or are revenue neutral. Both carbon taxes and cap-and-trade programs generate revenue making them attractive to policymakers who can then decide how to spend those revenues. Revenues are most commonly used to support research and development, fund financial incentives for adoption of cleaner technologies, or to return the

revenues to citizens in the form of climate dividends or offsets to income taxes [80]. There is an ongoing debate about the best use of public revenues gained from carbon pricing policies. For example, Jorgenson et al. [111] find that using carbon taxes to reduce capital tax rates will create the largest possible benefit relative to the costs of emissions control. On the other hand, Wang et al. [112] caution that reliance on carbon-pricing revenues may create a perverse incentive where governments that are dependent on carbon revenues choose tax levels that sustain continued revenues at the cost of maximized emissions reductions.

Policies that offer financial incentives to purchase or produce low CO_2 cement or concrete require public revenues. Policymakers often face difficulties finding long-term dedicated sources of revenue to support these financial incentives. As a result, subsidy programs can be relatively short-lived, and provide an unreliable signal to producers to invest in changing their operations to be less carbon intensive.

Finally, performance standards, product content requirements, or structural incentives are revenue neutral, neither generating nor requiring significant public revenues to operate. Thus, unlike carbon pricing mechanisms, these policy instruments cannot be used to support further emission reductions vis-à-vis a complementary financial incentive program or for other public funding needs.

5. Discussion and conclusion

Policymakers around the globe have adopted, and will continue to adopt, GHG abatement policies that impact cement and concrete sectors either directly or through upstream supply-chain pathways. To date, six cap-and-trade programs directly price emissions from cement manufacturing, while over a dozen carbon tax policies impact the transportation fuels, stationary fuels or electricity used in cement manufacturing. While no current command-and-control policies directly regulate emissions from cement manufacturing, several jurisdictions have passed carbon intensity standards for transportation fuels and a few have adopted low-carbon use standards for the construction industry.

When deciding which of these GHG policy instruments to adopt, policymakers should remain aware of several distinctive characteristics of the cement and concrete sector. Due to high capital investment requirements, cement manufacturing is often a concentrated industry, dominated by a few large firms. As a result, markets may not always be perfectly competitive which can influence the way that optimal GHG policies should be selected and implemented. In addition, the industry's heavy reliance of transportation and stationary fuels as well as electricity means that even when the cement manufacturing is not directly regulated its emissions may be significantly impacted by upstream GHG regulations on these fuels.

Our review of the literature suggests that carefully designed carbon pricing policies—such as cap-and-trade programs—may best achieve the targeted emission reductions, delivering the lowest social costs and the greatest certainty while also incentivizing technological innovations focused on future reductions. Part of the appeal of these GHG pricing policies is that they create continuous incentives across the supply chain to reduce the most emissions from processes with the least relative GHG abatement costs. Pricing policies can also generate revenue, which can fund research and development of advanced technologies. Technologies that abate process emissions such as alternative cements and CCU are particularly needed to fully decarbonize the concrete supply chain.

However, when making decisions about cap-and-trade allowance allocations or carbon tax designs, policymakers should consider that cement industries may be concentrated and thus already limit output below socially optimal levels. Moreover, because there is a demonstrable risk of GHG leakage, such as when imports of clinker, cement or concrete rise in response to local regulation, careful application of a border tax adjustment may also be desirable. To support these decisions, more empirical research is needed on how producers and consumers behave under different pricing policy designs, both in emerging and developed markets. Also, while not examined in this paper, policymakers should also consider the administrative feasibility, political feasibility, and equity implications of implementing pricing policies in their unique jurisdictions.

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